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# An approach to using snow areal depletion curves inferred from MODIS and its application to land surface modelling in Alaska

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## Abstract:

Snowcover areal depletion curves inferred from the moderate resolution imaging spectroradiometer (MODIS) are validated and then applied in NASA's catchment-based land surface model (CLSM) for numerical simulations of hydrometeorological processes in the Kuparuk River basin (KRB) of Alaska. The results demonstrate that the MODIS snowcover fraction $f$ derived from a simple relationship in terms of the normalized difference snow index compares well with Landsat values over the range $20 \leq f \leq 100\%$. For $f < 20\%$, however, MODIS 500 m subpixel data underestimate the amount of snow by up to 13% compared with Landsat at spatial resolutions of 30 m binned to equivalent 500 m pixels. After a bias correction, MODIS snow areal depletion curves during the spring transition period of 2002 for the KRB exhibit similar features to those derived from surface-based observations. These results are applied in the CLSM subgrid-scale snow parameterization that includes a deep and a shallow snowcover fraction. Simulations of the evolution of the snowpack and of freshwater discharge rates for the KRB over a period of 11 years are then analysed with the inclusion of this feature. It is shown that persistent snowdrifts on the arctic landscape, associated with a secondary plateau in the snow areal depletion curves, are hydrologically important. An automated method is developed to generate the shallow and deep snowcover fractions from MODIS snow areal depletion curves. This provides the means to apply the CLSM subgrid-scale snow parameterization in all watersheds subject to seasonal snowcovers. Improved simulations and predictions of the global surface energy and water budgets are expected with the incorporation of the MODIS snow data into the CLSM. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS Alaska; snow depletion curve; land surface modelling; MODIS; snow

## INTRODUCTION

Given its prevalence in high-latitude and altitude regions, snow represents a key component of the global hydrological cycle. With its radiative and thermal properties, a snowcover greatly affects the overlying air and the underlying ground. Snow reflects most of the incident solar radiation owing to its elevated albedo (up to 80% or more), which leads to a suppression of near-surface atmospheric temperatures (Ellis and Leathers, 1998). The insulating properties of snow, owing to its relatively low thermal conductivity, determine to a large extent permafrost conditions (e.g. Stieglitz *et al*., 2001, 2003). Through sublimation processes, a snowcover constitutes a sink of energy near the surface and a source of atmospheric moisture (Déry *et al*., 1998; Déry and Yau, 2002). During winter, snow acts as a temporary reservoir for water that may then be quickly released during the spring transition period, with meltwater contributing as much as 80% of the yearly discharge of some arctic streams and rivers (McNamara *et al*., 1998). Similarly, water resources for power generation and irrigation in many arid or semi-arid regions, such as the southwestern USA, depend largely on meltwater from alpine snowpacks (e.g. Sorooshian *et al*., 2002).

Recently, observational evidence has emerged suggesting ongoing changes in the state of seasonal snowcovers across North America and Eurasia. Brown and Braaten (1998) and Curtis *et al*. (1998) observed decreasing trends in snow depth, and Foster (1989) recorded trends towards an earlier spring snowmelt

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during the second half of the 20th century at Alaskan and Canadian arctic sites. In contrast, Ye *et al.* (1998) documented significant increases in snow accumulation in a zonal band between 60 and 70°N in northern Russia between 1936 and 1983. Changes in snowcover conditions are in part symptomatic of warmer near-surface air temperatures (Chapman and Walsh, 1993) that have led to modifications in continental precipitation patterns and phases (solid and liquid). These changes have important implications for all components of the global climate system, including the biosphere, cryosphere, and hydrosphere. For instance, enhanced wintertime snowfall in northern Russia has been observed to delay the spring melt, the onset of the growing season (Vaganov *et al.*, 1999), and to increase river discharge to the Arctic Ocean (Peterson *et al.*, 2002). An early onset of the spring melt in many regions of North America has prolonged the growing season such that the net primary production of vegetation has increased in recent years (e.g. Myneni *et al.*, 1997).

Although significant improvements have recently been achieved in the simulation of the large-scale (from 10 to 1000 km) spatial distribution of snow (e.g. Stieglitz *et al.*, 2001; Sheffield *et al.*, 2003), typical land surface models (LSMs) applied in regional climate models (RCMs) and general circulation models (GCMs) usually consider the snowcover to be spatially uniform within a model grid cell that often covers an area greater than 1000 km$^2$. In nature, however, considerable variability in snowcover characteristics (snow depth, snow water equivalent, albedo, etc.) exists owing to small-scale variations in topography, vegetation, and meteorological conditions. For instance, snowdrifts on the North Slope of Alaska may contain up to 20 times more mass than snow in non-drift regions (Sturm *et al.*, 2001). Thus, subpixel variability in snowcover can delay the onset of snow ablation from 2 weeks up to 2 months, with significant implications for the surface energy and water budgets (Arola and Lettenmaier, 1996; Luce *et al.*, 1998; Stieglitz *et al.*, 1999; Déry *et al.*, 2004).

We demonstrate the feasibility of using remote-sensing data of snowcover area to improve numerical simulations of land surface processes in an Alaskan watershed. Snowcover measurements inferred from the moderate resolution imaging spectroradiometer (MODIS) are first validated using an independent dataset. Then, snow areal depletion curves, defined here as the temporal evolution of the snowcover fraction for a given area (Hall and Martinec, 1985), are inferred from MODIS and provide the constraints for a subgrid-scale snow parameterization that has recently been developed for NASA's catchment-based LSM (CLSM; Koster *et al.*, 2000; Ducharne *et al.*, 2000). The goals of this study are twofold: (1) to validate the representation of subpixel snow by MODIS in the Kuparuk watershed and to correct the data for possible biases; (2) to apply the MODIS snow areal depletion curves to constrain the free parameters introduced by the CLSM subgrid-scale parameterization and to determine the benefits (if any) of using this information in numerical simulations of land surface processes in Alaska. To achieve these objectives, snowmelt for an 11 year period over the Kuparuk River basin (KRB) on the North Slope of Alaska is investigated.

## SUMMARY AND FUTURE WORK

We have demonstrated that subpixel (<500 m) values of snowcover fraction deduced from MODIS compared favourably with Landsat data. A mean absolute error in snowcover area of 0·07 and a coefficient of determination of 0·90 revealed the high level of accuracy achieved by the MODIS subpixel scheme applied to the North Slope of Alaska. The most prominent discrepancies between MODIS and Landsat measurements were found to occur at fractional values of <0·2. After a correction was applied to remove this bias, the MODIS data can be used to estimate snowcover area at all stages of the snowmelt period in the KRB of Alaska. Bias-corrected snow areal depletion curves for the spring of 2002 exhibited similar features to those inferred from snow-course measurements. A secondary plateau in snowcover area late during the melt period was associated with the presence of persistent snowdrifts on the arctic landscape. It was found that about 76% of the KRB was covered by a shallow snowpack and the remaining 24% by a deep snowpack. Application of these snowcover fractions in the CLSM subgrid-scale snow parameterization enhanced significantly the simulation of snowcover ablation and of freshwater discharge during the spring transition period for 11 years in the KRB.

Although we have demonstrated the feasibility of using MODIS data to constrain new parameters introduced by the CLSM subgrid-scale snow parameterization, this was achieved in a single basin. In other river basins, variations in the local topography, vegetation, and climate will interact to produce different levels of snowcover heterogeneity. As such, the area covered by shallow and deep snowcovers will vary from catchment to catchment in response to the local environment. To that end, a straightforward methodology that automatically extracts the shallow and deep snowcover fractions based on the evolution of the snow areal depletion curves inferred from MODIS will be applied in all watersheds subject to seasonal snowcovers. These fractions will then be used to provide the necessary parameters for the CLSM subgrid-scale snow parameterization. It is anticipated that incorporation of the MODIS data in the updated CLSM will improve simulations and predictions of the global surface energy and water budgets.

 